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Paleomagnetic investigation of rhyolite lava: Is rhyolite with clearly marked flow structure a high-fidelity geomagnetic field recorder?

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Rhyolite is a common volcanic rock; however, few studies have focused on the remanent magnetization of rhyolite lava, and few paleomagnetic studies have successfully investigated rhyolite lavas. We suspect that problems associated with paleomagnetic studies of rhyolite may be due to the nearly ubiquitous flow structure in rhyolite lava. In this study, we examined a thick rhyolite lava flow with clearly marked flow structure to assess its ability to record a consistent paleomagnetic direction, using material penetrated by two drill cores. Progressive thermal demagnetization isolated two magnetization components. A high-temperature component from each of the two cores yields inclinations that differ from each other. The low-temperature component had those that agreed with each other, and were also consistent with the direction expected from a geocentric axial dipole field. The modification of direction of the high-temperature component may be explained by post-magnetization acquisition tilting. The development of flow structure also leads to distortion of directions of the component, which is observed at stratigraphic positions where the volume fraction of light-colored parts of the flow structure $>30\%$. In the case of silicic lava, the low-temperature component may retain directions parallel to the ambient field direction at the time of lava emplacement.

Key words: Drill cores, flow structure, remanent magnetization, rhyolite lava.

1. Introduction

Volcanic rocks have long been recognized as good recorders of the geomagnetic field corresponding to the time of their formation. Because volcanic rocks are free from the effect of inclination shallowing that could be introduced from the compaction of sediments during syn- or post-depositional processes, volcanic rocks are considered to provide higher fidelity paleofield records than sedimentary rocks. In some recent studies, paleomagnetic directions derived from volcanic rocks were used to check the validity of coeval directions inferred from sedimentary rocks (e.g., Gilder *et al*., 2003; Hankard *et al*., 2007; Tan *et al*., 2010).

Rhyolite lava is a common volcanic rock in continental regions and can also be considered to be a useful source of paleomagnetic data. However, only few studies have focused on paleosecular variation, magnetostratigraphy or plate reconstruction analysis using the remanent magnetization of rhyolite lavas. A database of paleomagnetic poles for the East Asian continent since the Late Permian, for example, includes only two poles derived from rhyolite lavas (Enkin *et al*., 1992).

The reliability of remanent magnetization directions from rhyolite lavas would appear problematic, because few paleomagnetic studies have successfully investigated rhyolite lavas. Singer and Brown (2002) reported Pleistocene (0.9 Ma) directions from rhyolite lavas; one of three study sites was found to show a declination $\sim 180^\circ$ apart from the others, with consistent intermediate inclination of the same polarity between them. Hoshi (2002) presented Miocene (ca. 14 Ma) paleomagnetic data from rhyolite lavas showing large disagreement ($\sim 35^\circ$) of their direction from the expected paleomagnetic direction for the same region. In contrast, Ganerød *et al*. (2010) reported Paleocene (ca. 61 Ma) magnetization directions from rhyolite lavas, which were consistent with those from determined from the overlying and underlying basalts.

Being highly viscous, rhyolite lavas often show heterogeneous texture, unlike andesitic and basaltic lavas. Flow structure, one of the characteristics of rhyolite lava, may offer a clue about the changes in the direction of remanent magnetization in rhyolite lava during the development of the structure—heterogeneous texture in rocks may cause the deflection of the remanent magnetization to a direction different from the original one. In the case of metamorphic rocks, for example, the deflection of the direction of characteristic remanent magnetization was observed to be a function of the degree of anisotropy of magnetic susceptibility (Bartolomeu Raposo *et al*., 2003). The disagreement between the observed paleomagnetic direction of rhyolite lava and the expected one may be a function of the development of the flow structure.

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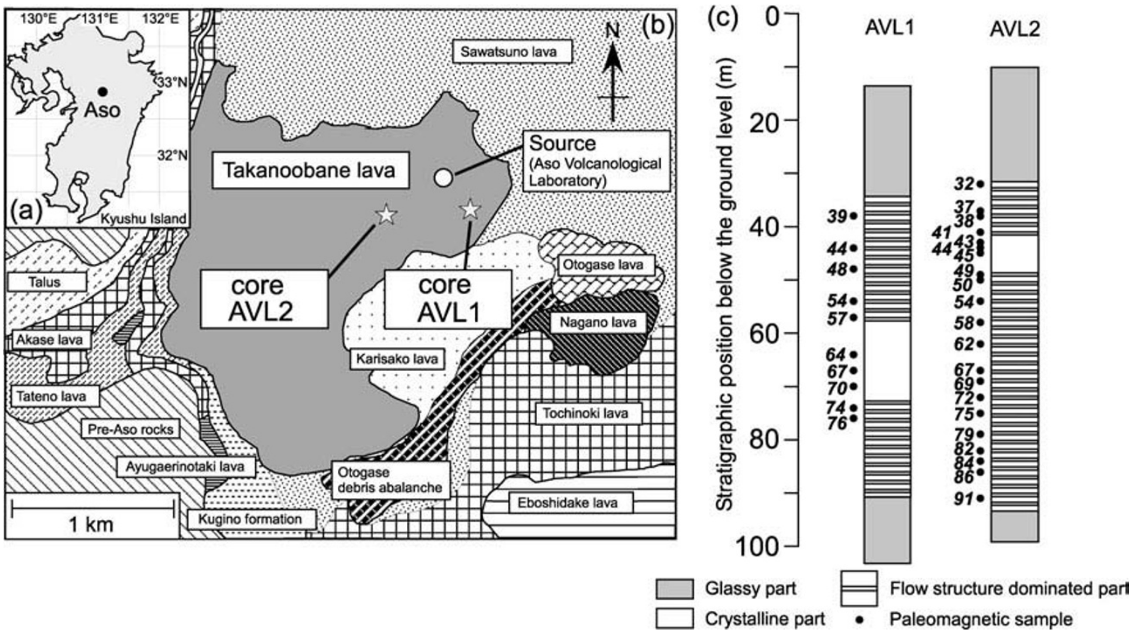

Fig. 1. (a) An outline map of Kyushu Island showing the location of Aso volcano. (b) Geologic map showing the distribution of the Takanoobane rhyolite lava and its source location, and the drilling sites (AVL1 and AVL2), after Furukawa *et al*. (2010). (c) Cross sections through AVL1 and AVL2 after Furukawa and Kamata (2005).

Another complication is the mechanical deformation of silicic lava during stages of cooling of lava flow after remanence acquisition; such deformation is independent of the development of the ductile texture (e.g., the flow structure). Nakada *et al*. (1995) observed that in many cases, the mechanical deformation of a silicic lava flow could initiate at areas proximal to the crater of lava domes, and then propagate to more distal areas; this is brought about by subsequent magma supply. This style of deformation of the lava flow may therefore cause the paleomagnetic direction of rhyolite lava to deviate from the expected one, regardless of the degree of development of the flow structure.

We conducted a paleomagnetic study of a thick rhyolite lava flow with clearly marked flow structure to evaluate if it records a consistent paleomagnetic direction, in both the vertical and horizontal perspectives. Two drill cores from the Takanoobane rhyolite lava of Aso volcano in Japan were used in this study. Because the Takanoobane rhyolite lava is completely penetrated by the drill cores, and because the two cores were drilled at different distances from the source, the cores are expected to provide an opportunity to define the vertical and horizontal variations in the direction of remanent magnetization. Generally, vertical sampling of rhyolite is limited to a certain stratigraphic interval because of its great thickness; this case study enabled us to illustrate not only localized deformation but also broader scale deformation features.

2. Takanoobane Rhyolite Lava

The Takanoobane rhyolite lava is located at the Aso caldera on Kyushu Island, Japan (Fig. 1(a)), and forms a dome-like structure. The lava has been K-Ar dated at 51 ± 5 ka (Matsumoto *et al*., 1991). The source of the lava is situated on a hill near the Aso Volcanological Laboratory of Kyoto University (32°53′7.77″N, 131°0′23.85″E) (Fig. 1(b)), and the lava flows down mostly westward to southwestward. The volume of the lava is estimated to be 0.14 km^3 (Miyabuchi *et al*., 2004), and bulk rock chemistry of the lava is 70 to 72 SiO_2 wt% (Miyoshi *et al*., 2005, 2011). We examined two continuous drill cores of the Takanoobane rhyolite lava (cores AVL1 and AVL2) provided by the Aso Volcanological Laboratory of Kyoto University. The two drill cores completely penetrate the lava; the thickness of the lava in cores AVL1 and AVL2 are 91.4 m and 91.0 m, respectively. The locations of AVL1 and AVL2 are 230 m and 340 m away horizontally from the source, respectively.

The Takanoobane rhyolite lava in the two cores is composed of an inner crystalline part, and marginal glassy parts (upper and basal glassy layers) (Furukawa and Kamata, 2005; Furukawa *et al*., 2010) (Fig. 1(c)). In both cores, the inner crystalline rhyolite shows a significant flow structure, characterized by light-colored bands a few millimeters to 3 cm thick. Furukawa and Kamata (2005) noted that the light-colored bands are made up of aggregates of deformed minute cavities 5–50 μm in diameter with a vesicularity of 40–50 vol%. The macroscopic shape of the minute cavity aggregates (the flow structure) in cores AVL1 and AVL2 are generally lenticular and tabular shapes, respectively. The flow structure in core AVL1 makes the angle of 10–30°, and $<20°$ to the horizontal plane in the upper and lower part of the crystalline rhyolite, respectively. The structure in core AVL2 makes the angle of 30–40°, 20–30°, and $<20°$ to the horizontal plane in the upper, middle and lower part, respectively (Furukawa and Kamata, 2005).

Ten samples from core AVL1 and twenty-one samples from AVL2 of the inner crystalline rhyolite were collected, and specimens with 25 mm diameter and 22 mm length were prepared from each sample for paleomagnetic analysis (Fig. 1(c)). Because these cores had been divided into 1-m sections for storage, and therefore, not azimuthally

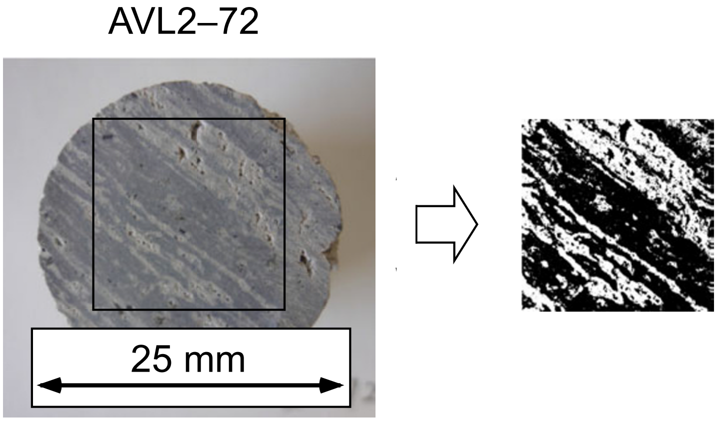

Fig. 2. Volume fraction of light-colored bands considered as a measure of the area ratio of white pixels to entire surface area.

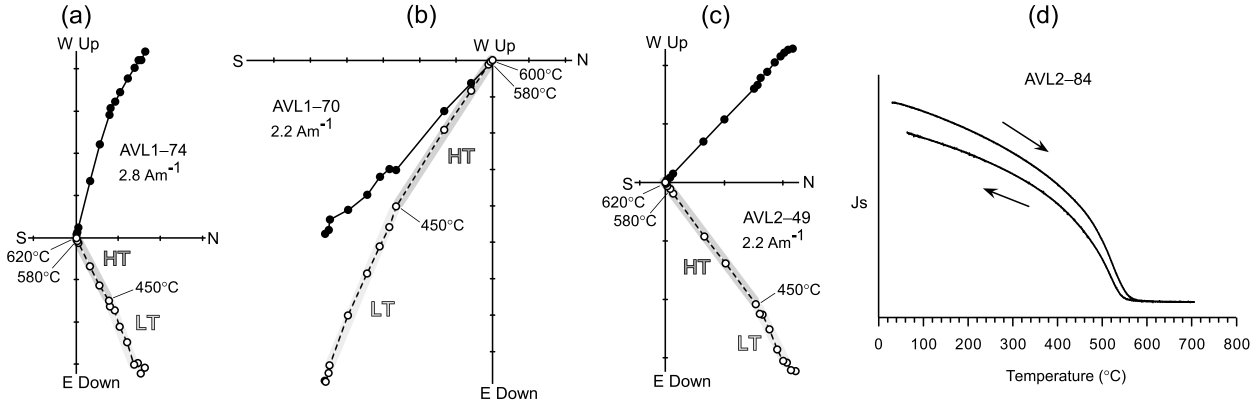

Fig. 3. (a–c) Orthogonal demagnetization diagrams of representative thermal demagnetization results of the Takanoobane rhyolite lava showing the high-temperature (HT) and low-temperature (LT) components. Solid and open symbols represent projection on horizontal and vertical planes, respectively. (d) Thermomagnetic analysis in air.

oriented, we arbitrarily defined the azimuth of 0° (i.e., the north) based on the dip direction of the flow structure for each sample. In addition, the degree of development of the flow structure for each specimen was measured according to the following method. Using digital-editing software, we simplified a photo image of the polished surface of a specimen to a black-and-white image, after which an area that consists of the light-colored bands was reduced to white (Fig. 2). The volume fraction of the light-colored bands was defined as the area ratio of white pixels, and was regarded as the degree of development of the flow structure for the specimen.

3. Paleomagnetism

Natural remanent magnetizations (NRMs) were measured with a Natsuhara SMM-85 spinner magnetometer at Okayama University. All specimens were subjected to progressive thermal demagnetization treatment using a Natsuhara TDS-1 thermal demagnetizer in steps of 50°C in the temperature range of 100–500°C. Demagnetization steps of 20 or 30°C were used in the temperature range above 500°C. Results for each specimen were plotted on orthogonal vector diagrams (Zijderveld, 1967) to evaluate their demagnetization behaviors. Principal component analysis (Kirschvink, 1980) techniques were used to estimate the directions of the observed magnetic components. Thermomagnetic analysis in a magnetic field of 0.8 T was carried out with an Eiko Curie balance at Kyoto University. Samples were heated to 700°C at a constant rate of 8°C min-1 and cooled at the same rate in air.

Initial NRM intensity of the rhyolite ranged between 7×10^{-1} and 3 A m^{-1}, with most NRM intensities on the order of 1 A m^{-1}. Thermal demagnetization revealed a low-temperature component, which was identified after the removal of unstable remanence in the first two or three steps of treatment (∼150°C). The most commonly observed maximum unblocking temperature of this low-temperature component was 450°C (Fig. 3). After elimination of the low-temperature component, a high-temperature component decays toward the origin. A large fraction of the high-temperature component is demagnetized by 580°C, and little change in direction is observed after demagnetization at temperatures above 580°C, suggesting that the high-temperature component largely resides in magnetite, with a small contribution from hematite. The component that decays to the origin is generally unblocked at temperatures between 600°C and 660°C.

The thermomagnetic results show a single Curie temperature of 560°C that is indicative of low-Ti titanomagnetite, and show that the presence of hematite is not demonstra-

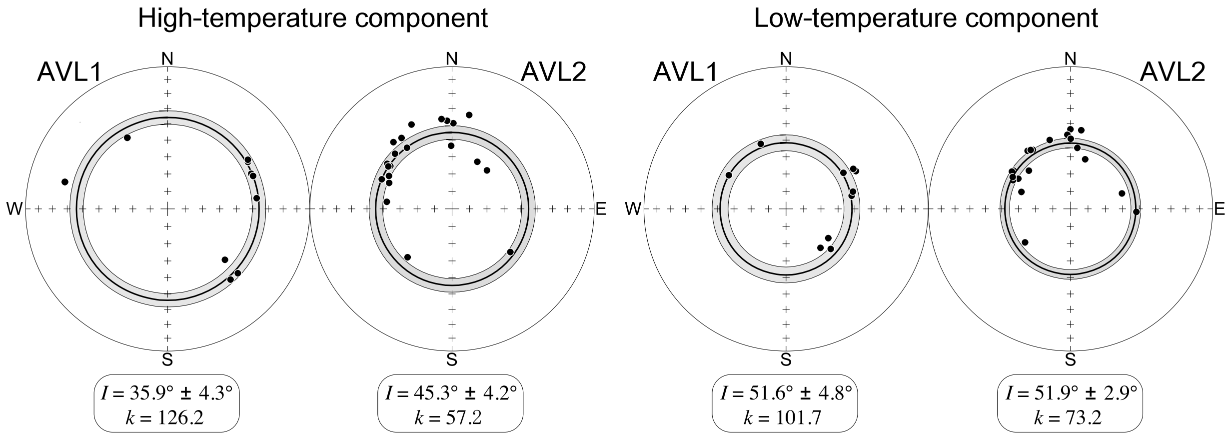

Fig. 4. Equal area projections of the directions of magnetization of the high- and low-temperature components for samples from cores AVL1 and AVL2. Solid symbols represent projection onto the lower hemisphere. Solid bold circles denote mean inclination (with associated 95% confidence limits).

bly significant. The single Curie temperature suggests that both the low- and high-temperature components reside essentially in a single-phase titanomagnetite.

The paleomagnetic directions of the high- and low-temperature components from cores AVL1 and AVL2 is illustrated in Fig. 4. In each projection, directions are characterized by consistent inclinations and variable declinations, which could be due to a variation in the dip direction of the flow structure at the time of emplacement of the lava. That is, the dip direction may not be consistent throughout the lava section. Accordingly, an inclination-only statistics method (McFadden and Reid, 1982) was employed to determine a mean inclination. From this, the fidelity of the acquisition of remanent magnetization direction was examined. Mean inclinations of the high-temperature component for cores AVL1 and AVL2 were found to be $35.9° \pm 4.3°$ and $45.3° \pm 4.2°$, respectively. The two inclinations are significantly different from each other at the 95% confidence level. Mean inclinations of the low-temperature component for cores AVL1 and AVL2 were found to be $51.6° \pm 4.8°$ and $51.9° \pm 2.9°$, respectively. They are indistinguishable from each other, and also indistinguishable from the direction expected from a geocentric axial dipole field at the sampling site ($I = 52.3°$) at the 95% confidence level.

4. Discussion

The Takanoobane rhyolite lava yields two remanent magnetization components, both of which are considered to be of thermoremanent magnetization (TRM) origin. These components are considered primary in origin because of the following reasons. (1) A 51 kyr exposure in the magnetic field is expected to result in a laboratory unblocking temperature of a viscous overprint below 200°C for magnetite (Pullaiah *et al.*, 1975), which is less than that of the observed low-temperature component by >250°C. (2) Optical microscopic observations of polished thin sections of rhyolite under transmitted and reflected light indicate little or no chemical alteration after its emplacement in both magnetic minerals and other phenocrysts. (3) The thermomagnetic results show a single magnetic phase that is indicative of low-Ti titanomagnetite. These observations provide evidence for a primary origin of the observed remanences.

The high-temperature components from both cores, whose directions differ from each other, do not retain inclinations parallel to the ambient geomagnetic field direction at the time of lava emplacement. Conversely, the low-temperature component from both cores gives records of inclinations along the ambient field direction, as shown by the coincidence of direction between both cores and the axial dipole field. For each core, the amount of inclination deviation of the high-temperature component from the low-temperature component is calculated—the mean inclination of the high-temperature components of cores AVL1 and AVL2 is $15.7° \pm 6.4°$ and $6.6° \pm 5.1°$, respectively, shallower than that of the corresponding low-temperature components.

There appears to be, in particular for core AVL1, consistently shallow inclinations in the high-temperature component throughout the section (Fig. 4), within which dip direction of the flow structure varies with depth in the flow as mentioned above. Figure 4 is drawn by orienting the dip direction of the flow structure toward 0°, and, therefore, it could be considered that a consistent inclination was acquired by the rhyolite at the time of lava formation, regardless of the attitude of the flow structure relative to the ambient field direction. These observations are interpreted to demonstrate that the shallow-inclination component cannot be attributed to the slope of the flow structure, and in some cases to its associated anisotropy.

The shallow-inclination component can probably be attributed to tilting associated with the development of the rhyolite dome. Endogenous growth of lava domes occurs by the subsequent supply of highly viscous magma and facilitates uplifting and tilting of dome materials (Nakada *et al.*, 1995). Tilting occurs to a greater degree at areas proximal to the crater than at distal ones. Therefore, tilting is expected to have taken place more significantly in core AVL1 (taken 230 m from the source), compared to core AVL2 (340 m from the source). Because cores AVL1 and AVL2 are located slightly to the south of the crater, the sites of the cores are anticipated to be tilted southward due to endogenous growth of the lava dome, which would result in shallowing of the north-directed magnetization that was already acquired.

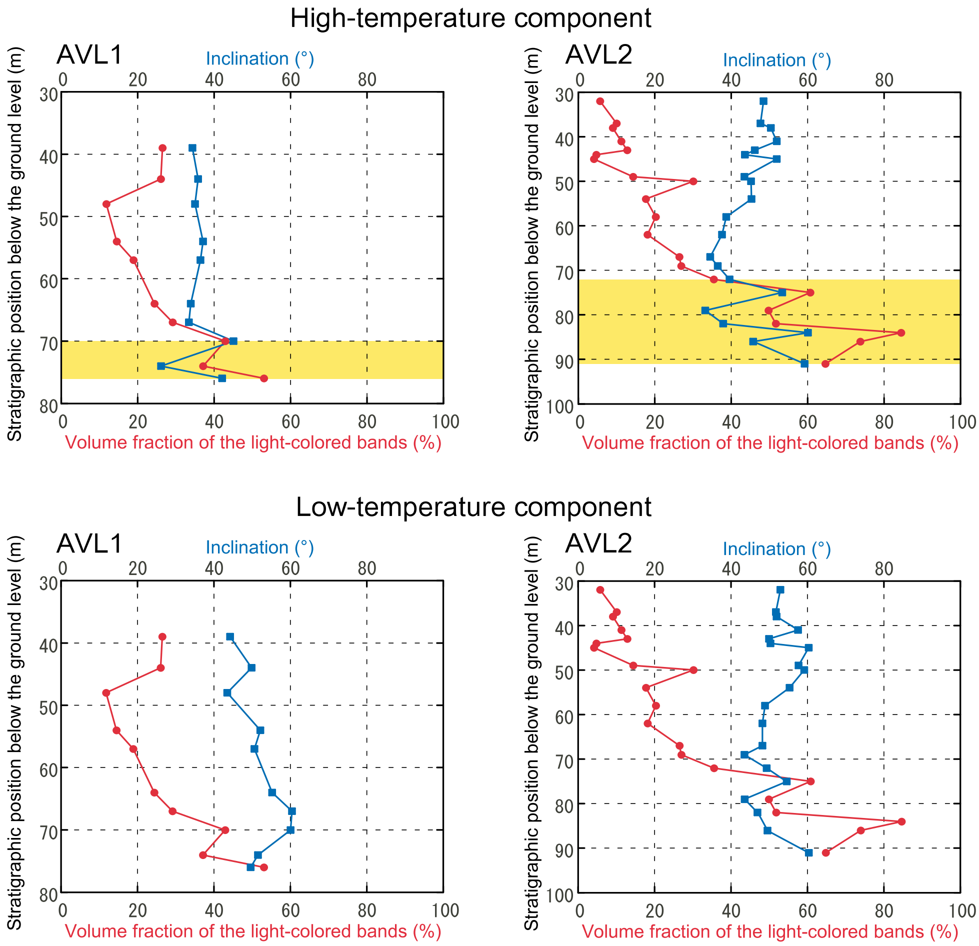

Fig. 5. Plots of inclination and volume fraction of the light-colored bands as a function of the core depth. For the high-temperature component of each core, the yellow colored area denotes the stratigraphic position with the volume fraction of the light-colored bands >30%.

There appear to be two other possible explanations for the shallow-inclination component—one is flow brecciation, and the other is localized deformation along the lava margin. (1) Breccia clasts may have been tilted toward flow margins and could have resulted in shallow inclinations. However, it would be expected that the shallow inclinations would be exclusively at the upper and basal part of silicic lava flow (Manley and Fink, 1987; Smith, 1996). In the present case however, the shallow inclinations are observed in the entire flow. (2) Core AVL1 is located at marginal area of the lava flow and may have suffered tilting due to tension that arises at the margin. However, the inclination shallowing is also observed even at the site of core AVL2 that is located on the main stream of lava flow continued down southwestward (Fig. 1). Therefore, we infer that the high-temperature component was produced by tilting of the lava dome due to endogenous growth, after the lava had been cooled to a temperature as low as 450°C.

Detailed examination of the inclination from both cores shows a fluctuation in the high-temperature component at the basal part of the crystalline rhyolite namely, greater than ~70 m below the ground level for each core (Fig. 5). In this part of the flow, inclination values for cores AVL1 and AVL2 fluctuate within the ranges of 26.1–45.1° and 33.2–60.1°, respectively, which are large when compared to those from samples above ~70 m below the ground level, these being within the ranges of 33.4–37.1° and 34.5–51.9° for AVL1 and AVL2, respectively. We also observe that the basal part of the flow below ~70 m from the ground level has a relatively high volume fraction of light-colored bands (greater than 30%, yellow colored area in Fig. 5). This could be interpreted as being an effect of the modification of remanence direction as a result of the development of flow structure, because the light-colored bands are the fundamental products of the development of the flow structure (Furukawa *et al.*, 2010). Because the high-temperature component displays linear characteristics during progressive thermal demagnetization (Fig. 3), the modification appears to have occurred once at around 450°C during the cooling. The light-colored bands show the vesicularity of 40–50 vol% and are composed of aggregates of significantly deformed minute cavities (Furukawa *et al.*, 2010), suggesting that the zones where the flow structure develops could have space to accommodate deformation and compaction, likely leading to distortion of remanence directions, in response to subsequent lava intrusion.

One may note a fluctuation in the inclination of the low-temperature component with depth in the flow from both cores (Fig. 5). However, the variation in inclination for the low-temperature component is smaller than that for the high-temperature component. The inclination of the low-temperature component for both cores varies by 16.9° from minimum to maximum, while that of the high-temperature component for cores AVL1 and AVL2 varies by 19.0° and 26.9°, respectively. Therefore, we interpret this result to show that the rhyolite lava did not suffer deformation after acquisition of magnetization to an extent sufficient to lead to fluctuation in inclination of the low-temperature component.

Based on the character of the high-temperature components of magnetization in our samples, two factors are considered to be responsible for the modification of the remanence direction in the rhyolite lava—one is tilting due to the endogenous growth of a lava dome, which is a common phenomenon during silicic lava eruption, and the other is the development of the flow structure, which is marked by a higher volume fraction of the light-colored bands.

In contrast to the high-temperature component, the low-temperature component is interpreted to retain the direction parallel to the ambient geomagnetic field direction at the time of lava emplacement. Although remanences that mirror ancient geomagnetic field direction are generally observed over a range of high laboratory unblocking temperatures during thermal demagnetization and often appear after removal of lower-temperature components, this does not appear to be the case for this rhyolite lava flow. In the case of silicic lava, it is considered that the direction of lower-temperature components may more accurately reflect that of the ambient geomagnetic field at the time of lava emplacement rather than higher-temperature components. In other words, we would identify the lower-temperature component as the remanence acquired after any deformation has been completed.

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